

Experimental study of the influence of different resonators on thermoacoustic conversion performance of a thermoacoustic-Stirling heat engine

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Abstract

In this paper, an experimental study of the effect of the resonator shape on the performance of a traveling-wave thermoacoustic engine is presented. Two different resonators were tested in the thermoacoustic-Stirling heat engine. One resonator is an iso-diameter one, and the other is a tapered one. To have a reasonable comparison reference, we keep the same traveling-wave loop, the same resonant frequency and the same operating pressure. The experiment showed that the resonator shape has significant influence on the global performance of the thermoacoustic-Stirling heat engine. The tapered resonator gives much better performance than the iso-diameter resonator. The tapered resonator system achieved a maximum pressure ratio of about 1.3, a maximum net acoustical power output of about 450 W and a highest thermoacoustic efficiency of about 25%.

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1. Introduction

Heat energy with temperature difference may lead to self-excited acoustical oscillation under appropriate conditions, which is well known as thermoacoustic oscillation. One of the most important applications based on the self-excited thermoacoustic oscillation is a thermoacoustic prime mover. A traveling-wave thermoacoustic engine has been paid more and more attention in recent years due to its potential of realizing higher efficiency than a standing-wave thermoacoustic heat engine [1,2]. The first thermoacoustic-Stirling heat engine developed by Backhaus and Swift in 1999 achieved a thermal efficiency of 30% for a pressure ratio of around 1.2 [3]. More recently, Luo et al. proposed an energy-focused thermoacoustic-Stirling heat engine that can be capable of increasing its pressure ratio up to about 1.3, and some preliminary result

was reported in a brief communication [4]. To understand its operating mechanism more deeply, extensive experimental tests regarding acoustical power and thermoacoustic conversion efficiency have been done on the energy-focused thermoacoustic heat engine. Moreover, a lot of comparison experiments on the iso-diameter and tapered resonators have been conducted. Details of the work will be described in the following of the paper.

2. Experimental setup

A qualitative explanation for using a tapered resonator to increase the performance of thermoacoustic heat engines was already described, which can be found elsewhere [4]. The schematic of the energy-focused, thermoacoustic-Stirling heat engine (referred to EF-TASHE) is shown in Fig. 1. Actually, the tapered resonator can effectively suppress excitation of higher mode oscillation and let thermoacoustic conversion focus on the fundamental mode oscillation, so we call the thermoacoustic-Stirling heat

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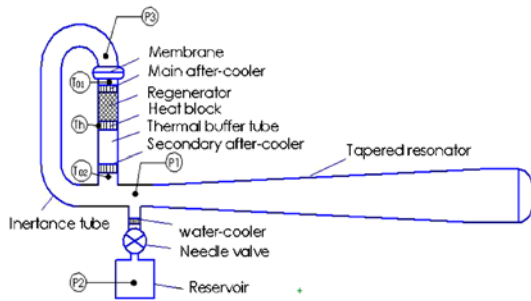


Fig. 1. The energy-focused thermoacoustic-Stirling heat engine.

engine as the energy-focused thermoacoustic-Stirling heat engine. In the traveling-wave loop, all diameters of components are 80 mm. The length of the regenerator, thermal buffer tube and the feedback tube are 78 mm, 240 mm and 1500 mm, respectively. The regenerator is filled with 120-mesh steel-stainless screens with a porosity of about 0.68. The feedback tube acts not only as an inertance tube but also as a compliance. The resonator is made of two parts: a tapered pipe and an iso-diameter reservoir with an end cap, and it is basically designed as a quarter wavelength system. The tapered pipe is 3 m long and has a diameter varying gradually from 80 mm to 200 mm, corresponding to a tapering angle of about 1.14° . In fact, the concrete structure parameters about the tapered resonator are based on our CFD simulation, which can be found elsewhere [5]. The reservoir is 200 mm in diameter and 500 mm in length and is connected to the larger end of the tapered pipe by welding.

To measure acoustical power and thermoacoustic conversion efficiency, the RC load method was used [6]. Actually, the RC load is a combination of an 8 mm-diameter needle valve and a 5.4-L reservoir. It is adjacent to the tee joint of the traveling-wave loop. The net acoustical power delivered to the RC load is measured by the two pressure sensors P1 and P2 before and after the valve. In the thermoacoustic heat engine, the point with the highest oscillating pressure amplitude is located nearby to the main after-cooler. Thus, the third pressure sensor P3 is used to monitor the highest-pressure point. In addition, three K-type thermal-couples are used to measure the heating temperature of the heater block, the cooling temperatures of the two after-coolers. With these parameters, thermoacoustic conversion efficiency of the thermoacoustic heat engine can be evaluated. The thermoacoustic conversion efficiency is defined as the ratio of the acoustical power divided by the heating power.

On the other hand, an iso-diameter resonator cavity is also tested to compare with the tapered resonator cavity. When an iso-diameter resonator cavity is used, the thermoacoustic heat engine becomes a conventional thermoacoustic-Stirling heat engine (referred to C-TASHE). The EF-TASHE has a resonant frequency of about 87 Hz. To have a reasonable base of comparison, the iso-diameter resonator also has a diameter of 80 mm and its length is chosen to achieve a resonant frequency of about 87 Hz, too.

Under the same resonant frequency, the EF-TASHE and C-TASHE's traveling-wave loops should operate without any difference. Then, we think that the difference of thermodynamic performance between them is just caused by their different resonators. By means of the method, one can know which resonator works better and how good it is.

3. Experimental results and discussion

Extensive test on the two thermoacoustic-Stirling heat engines have been done with helium gas under different averaged pressures. From our experiments, the EF-TASHE gives higher pressure ratio than the C-TASHE; for instance, for the case of 3.0 MPa mean pressure and 4.0 kW heating power, the EF-TASHE achieves a pressure ratio of above 1.17 while the C-TASHE only achieves a pressure below 1.15. Fig. 2 shows the comparison of net acoustical power for the two types of thermoacoustic-Stirling heat engines. It also can be seen from the figures that the EF-TASHE gives higher acoustical power output than the C-TASHE.; for instance, for a heating temperature of about 600°C , the EF-TASHE is capable of outputting about 200 W while the C-TASHE only outputs about 160 W. It is noted here that the acoustical power is measured by changing the acoustic RC-load. Thus, for a given mean pressure and heating power, the pressure ratio and heating temperature may both vary with RC-load. Thus, only thermal efficiency can really indicate which is better. That is why we further give the thermal efficiencies of the two thermoacoustic heat engines which are shown in Fig. 3. As seen from Fig. 3, the EF-TASHE indeed gives a better performance than the C-TASHE. Generally, the EF-TASHE can improve thermoacoustic conversion efficiency by about 20–80% more or less. Especially, at the most efficient point, the EF-TASHE achieves a thermal efficiency of about 18%; moreover, if including the acoustical power dissipated by the resonator [6], the thermoacoustic traveling-wave loop is capable of achieving about a thermoacoustic conversion efficiency of about 25%.

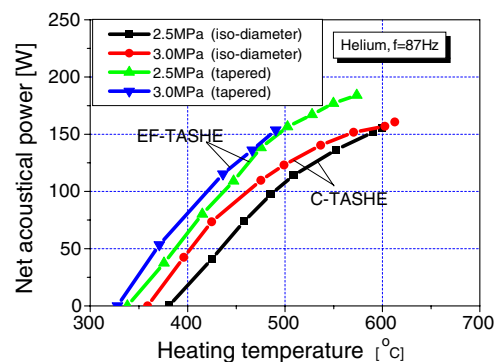


Fig. 2. Net acoustical power vs. heating temperature under different averaged pressures for the two resonators.

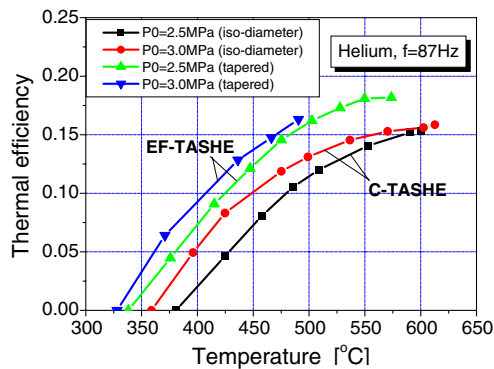


Fig. 3. Thermoacoustic conversion efficiency vs. heating temperature under different averaged pressures for the two resonators.

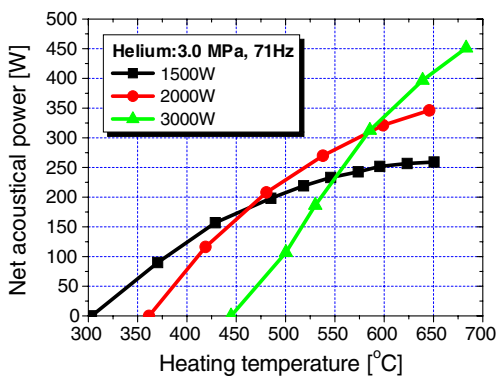


Fig. 4. Net acoustical power output vs. heating temperature under different heating powers.

Besides having performed the comparison experiment described above, we also tested a longer tapered resonator. The longer tapered resonator is about 4 m long, so it operates at a lower resonant frequency of about 71 Hz. For this resonant frequency, we have not made a comparison with an iso-diameter resonator. The longer EF-TASHE achieved a pressure ratio of above 1.30 for an averaged pressure of 1.52 MPa, which was reported in Ref. [4]. Fig. 4 gives the net acoustical power output dependent of the heating temperature under 3.0 MPa mean pressure. It can be seen that the acoustical power output goes up as the heating temperature increases. When the heating power is 3.0 kW, the energy-focused heat engine can deliver a net acoustical power of about 450 W. In fact, the total power produced by the traveling-wave loop should be much larger than the net output.

The reason is that there is still some part of acoustical power dissipated by the resonator.

4. Conclusion

The energy-focused thermoacoustic-Stirling heat engine is studied in this paper. This energy-focused thermoacoustic-Stirling heat engine uses a specially tapered resonator to improve the performance of the heat engine by decreasing nonlinear losses. Comparison experiment with the iso-diameter and tapered resonators is made. These tests are concerned with pressure ratio, acoustical power output and thermoacoustic conversion efficiency under different working pressures and heating powers. All of the experimental result shows that the tapered gives better performance. Especially, when using the tapered resonator, the thermoacoustic-Stirling heat engine can achieve a highest-pressure ratio of above 1.3 with 1.52 MPa helium gas, and a net acoustical power output of about 450 W under a heat power of 1.5 kW. In addition, the EF-TASHE can improve thermoacoustic conversion efficiency over the C-TASHE by about 20–80%. However, further study still needs to be made on this topic.

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